P. A. MORETON

AEA Technology
Thomson House
Risley
Warrington, WA3 6AT
United Kingdom

R. W. S. BARNES

The Felixstowe Dock and Railway Company
Tomline House
The Dock, Felixstowe
Suffolk, IPII 8SY
United Kingdom

R. MERRIFIELD

Health and Safety Executive
Magdalen House
Stanley Precinct, Bootle
Merseyside, L2O 3QZ
United Kingdom

THE ROLE OF RISK ASSESSMENT IN PROMOTING SAFETY
PAPER 2: HANDLING OF EXPLOSIVES IN PORTS

INTRODUCTION

In 1993, large quantities of ammunition were moved through a number of commercial ports in the UK following the implementation of various military drawdown programs. These movements were subject to the normal statutory controls governing the handling of explosives in the UK, and the drawdown programs for the year were completed without incident. The statutory controls have been designed both to guard against accidents and to ensure limited consequences in terms of numbers of fatalities and damage to property in the unlikely event of accidental explosion. The success of these statutory measures applied to commercial ports is demonstrated by an excellent safety record, which shows the occurrence of only one very minor (non-fatal) explosive event m post-war times.

However, all operations involving transportation of dangerous goods cannot be entirely free of risk, albeit that this risk may be very low. To optimize the safety of such operations it is desirable to carry out a detailed examination of the risks involved and implement any

Report Documentation Page		*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **AUG 1994**	2. REPORT TYPE	3. DATES COVERED **00-00-1994 to 00-00-1994**
4. TITLE AND SUBTITLE **The Role of Risk Assessment in Promoting Safety -Paper 2: Handling of Explosives**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **AEA Technology,Thomson House,Risley,Warrington, WA3 6AT, United Kingdom,**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES **See also ADM000767. Proceedings of the Twenty-Sixth DoD Explosives Safety Seminar Held in Miami, FL on 16-18 August 1994.**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**15**	

measures necessary to reduce the risks to a level "as low as reasonably practicable" (ALARP). Quantitative risk assessment (QRA) provides a tool to help achieve this goal, though this is currently not a statutory requirement for licensed ports in the UK.

The risks of moving explosives through UK ports have recently been studied in detail using the techniques of QRA and a report on this work is due to be published in the coming months. This paper describes the study of the risks arising from movements of ammunition through one particular port, the Port of Felixstowe, undertaken as part of the 1993 military drawdown program. The paper summarizes the results obtained and discusses measures taken to optimize the safety of such movements.

THE SUBJECT OFTIIE STUDY

The Port of Felixstowe

The Port of Felixstowe is the UK's busiest container port, handling in excess of one million containers (twenty-foot equivalent units) each year. The port also has facilities for handling Roll-on-roll-off and break-bulk cargo and an oil jetty for importing and exporting bulk petroleum and chemical products. The port also has significant passenger ferry services.

All of the terminals at Felixstowe are licensed to handle explosives though in practice most of this trade is handled at the most isolated terminal in the port, which is known as Trinity Terminal. Trinity is licensed to handle relatively large quantities of explosives - up to 2OOte NEQ of substances or articles of Hazard Division 1. 1*. All of the military shipments that passed through the port as part of the 1993 drawdown program were (un)loaded at Trinity.

The Method Emploved for Moving Explosives

All of the ammunition moved through the port was packed inside 150 freight containers. At no stage during the handling operations were containers opened or palletized loads of ammunition removed. The containers remained sealed during passage through the port. The movement of explosives through ports in containerized loads offers certain advantages over the traditional break-bulk mode of loading and unloading: less handling is involved, the operation is quicker, it is easier to remove cargo from a ship in the event of an emergency, the freight container provides some degree of fire resistance, fewer workers are required and hence fewer people are exposed to risk. Export operations proceeded in the following manner:

(a)   The containers were brought into the port by rail on specially commissioned trains - no freight was carried on these trains other than ammunition. The trains were unloaded at the port's rail terminal by container gantry cranes, which transferred the containers directly from rail vehicles on to road trailers -one container per trailer.

----
* The system of control imposed on explosives movements through ports in Great Britain is based on the well established principle of quantity distances, ie restrictions are placed on the types and quantities of explosives that may be moved so as to ensure limited consequences in the event of an accident. Explosives limits for terminals within ports are set out in formal licenses issued by the UK Health and Safety Executive.

(b)   The trailers were driven about a mile through the port to the berth at Trinity. Here, container gantry quay cranes directly transferred containers from the trailers on to dedicated ammunition ships.

(c)   The ships departed from the berth as soon as possible after the loading operation had been completed, thus minimizing the amount of time the explosives were present in the port.

QUANTITATIVE RISK ASSESSMENT METHODOLOGY

The risks of moving ammunition through the port were studied using the techniques of QRA. In essence, QRA is a technique for undertaking a systematic analysis of the risks of a hazardous activity, evaluating the significance of those risks and providing information for use in decision-making on safety issues. The technique can be conveniently subdivided into two procedures: risk analysis and risk evaluation. Risk analysis is a technical procedure which attempts to estimate the level of risk posed by a hazardous activity, while risk evaluation is essentially an interpretative procedure which attempts to assess the acceptability of the estimated risks.

The risks assessed in the present study were those arising from shipments of ammunition through the Port of Felixstowe as part of the military drawdown program for 1993. The risks were analyzed employing the classical form of risk analysis, in which accident causes, likelihood and consequences were determined and combined to produce estimates of risk. In the present study this entailed a five-step approach in which:

(i)   the potential causes of explosives events were identified;

(ii)   estimates were obtained for the likelihood of these events;

(iii)   estimates were derived for the numbers of people who would be killed in these events;

(iv)   estimates for likelihood and consequences of explosives events were combined to produce estimates of risk;

(v)   potential risk reduction and mitigation measures were evaluated to provide insights to help achieve optimum safety.

The risk results were expressed in the form of FN curves which show the estimated annual probability of events (F) resulting in N or more fatalities.

Uncertainty in risk analysis

Although the results of a risk analysis are expressed in quantitative terms, it is widely accepted that risk analysis is not an exact science and its results are inevitably subject to uncertainty. This uncertainty arises from many sources, including, in general, doubts about whether all potentially significant causes of accidents have been identified, the use of simplified models to represent complex

systems, the lack of appropriate data from which to derive frequency estimates for various hypothetical accidents, incomplete understanding of how systems respond in accident conditions and lack of accurate and comprehensive models on which to base estimates for the consequences of accidents.

A number of techniques have been developed to deal with uncertainty in risk analysis. The approach adopted in the present study has been to use, wherever possible, realistic best-estimate values for the various parameters appearing in the mathematical equations (for example, the probability that a particular type of explosives would bum to explosion following ignition), but wherever there was any doubt about the exact value of a parameter, some overestimate has been preferred to produce a conservative output. The overall aim has been to produce results that are likely to err on the side of caution but which at the same time are not grossly pessimistic. Sensitivity tests have also been carried out to determine the variability of the overall results to the assumptions made. This approach has been defined by the UK Health and Safety Executive as the "cautious best estimate approach" to risk analysis[1].

The potential causes of explosives events

Experience has shown that explosives cargo can be accidentally initiated during transportation in one of two ways:

(i)   Following errors or breaches in regulations that result in unsafe explosives entering the transport chain, with the result that initiation occurs spontaneously without the involvement of explosives cargoes in external accidents, such as falls of loads from cranes or ship fires.

(ii)   As a result of the involvement of explosives cargo in energetic accidents - for example a tmck collision that results in ignition of a fuel fire.

Unsafe explosives items are defined as items that have been badly designed, manufactured, packaged or that are in a deteriorated condition. The danger posed by such items is illustrated by a number of accidents that have occurred in the UK[2]. The most recent such incident occurred in 1989, when an explosives-carrying road tmck blew up in an industrial estate following an initiation of some unsafely packaged fUseheads[3]. Experience indicates that unsafe explosives are as likely a source of explosive events during transportation as energetic accidents.

Various types of energetic accidents could, in theory, bring about an initiation of explosives cargo. The different types of energetic accidents which could foreseeably occur in ports and pose a threat to the safety of explosives cargo were identified by the well-established technique of Hazard and Operability (HAZOP) Study[4]. Many different types of accident scenarios were identified in this study, but nine in particular, involving fire or impact, were considered to pose the dominant threat:

Fire Accidents

(i)   train fires

(ii)   road trailer fires

(iii)   ship fires

Impact Accidents

(i)   train crashes and deraihnents

(ii)   road trailer crashes and collisions

(iii)   falls of loads from cranes

(iv)   ships striking vessels loading explosives

(v)   collisions between explosives carrying vessels and other ships.

The involvement of explosives cargo in any of the above types of accidents would not necessarily result in an explosive event. These accidents can be regarded as "dangerous occurrences" that would pose a threat to the safety of explosives cargo but would not necessarily result in the initiation of an explosion or a fire within an explosives load.

Rates for dangerous occurrences

Estimates for the rates with which the above types of accidents might potentially occur in ports were derived from various sources of accident data. In many cases, no records were found for dangerous occurrences involving explosives cargoes specifically, and this meant that accident rates had to be derived from accident data covering a wider range of cargoes than explosives. In general, the use of such rates could be expected to produce conservative results as more care tends to be exercised when explosives (as opposed to non-hazardous cargoes) are handled. An example of the type of data analysis performed is set out below for the case of crane accidents.

The Port of Felixstowe had records for five cargo-damaging accidents involving uncontrolled descent of loads from container gantry cranes (explosives cargoes were not involved in any of these accidents). These accidents occurred in a period in which approximately 4,699,000 crane lifts were performed. A mean accident rate can be derived from these statistics as follows: $5/4,690,000 = 1. 10^{-6}$ per crane lift, ie one chance in a million of a cargo-damaging accident per crane lift. This rate is, of course, subject to a certain amount of statistical uncertainty; assuming a Poisson distribution, the 90% confidence limits are:

Upper bound value	=	2.10^{-6} per crane lift
Mean value	=	1.10^{-6} per crane lift
Lower bound value	=	4.10^{-7} per crane lift

The upper bound value was used in the further stages of the study to ensure that risks were not underestimated. **

** Data collated from two other ports provided a certain amount of corroboration for this value. The operators of one of these ports reported one cargo-damaging crane accident in a period in which approximately 149,000 container lifts were performed (mean accident rate = 7. 10-6 per crane lift), while the operators of ihe other port reported three crane accidents, in which four containers were damaged in total, in a period in which approximately 1,000,000 container lifts were performed (mean accident rate = 4. 10-6 per crane lift). Combining the data obtained from all three ports produced a mean accident rate of 10/5,839,000) = 2. 10-6 per crane lift.

Similar analyses were carried out to obtain estimates for the rates for the other types of dangerous occurrence listed in Section 3.2. As noted previously, the involvement of ammunition in these types of incidents would not inevitably result in an explosion. In general, ammunition is designed and packaged to standards that ensure that initiation would be unlikely in the event of its involvement in the types of impact accidents that could foreseeably occur in ports, though some types of ammunition are more robust than others.

It is generally recognized, however, that fire poses a greater threat to the safety of explosives loads, and that most ammunition classified as HD 1. 1 or HD 1.2 could be expected to explode on exposure to fire, though burn to explosion times would depend on rates of heating and could vary between items. Ammunition should ideally be designed and packaged to standards that ensure it would withstand initial fire attack and thus allow time for people to be evacuated from the scene of a fire accident before the occurrence of an explosive event. In some circumstances it may be possible for action to be taken against a fire before it escalates to threaten an explosives load. Prompt action by emergency response teams would be required in such situations. In fact, the Port of Felixstowe has its own fire brigade which can be in attendance at incidents within a few minutes of the alarm being raised.

Values for the conditional probability that an explosives load would initiate, given its involvement in a cargo-damaging accident, have been derived from both accident data and trials data[***]. Rates for initiating events have been derived by multiplying rates for dangerous occurrences by conditional probabilities of initiation. In some cases rates for dangerous occurrences derived from generic accident data have been modified by use of expert judgement to take account of fire-fighting arrangements at the port. The following values were obtained for rates of initiating events:

Rates for Initiating Events: Fire Accidents

road trailer fires:	2.10^{-10} per vehicle-km
train fires:	4.10^{-9} per container arrival
container ship fires:	2.10^{-8} per ship arrival

Rates for Initiating Events: Impact Accidents

train derailments /collisions:
(munitions incorporating rocket motors) 3.10^{-9} per container arrival
(iron bombs) 3.10^{-11} per container arrival
(other munitions) 3.10^{-10} per container arrival

*** In some cases the values derived were statistical upper limits based on zero incidents in a large number of trials. It follows that these values may overstate the chance of an explosion in the event of an accident. While the use of such values is in keeping with the conservative best estimate approach to the risk analysis (see Section 3.1) further work might justify the use of lower values

road trailer crashes/collisions
(munitions incorporating rocket motors) 1.10^{-9} per vehicle-km
(iron bombs) 1.10^{-11} per vehicle-km
(other munitions) 1.10^{-10} per vehicle-km

crane accidents:
(munitions incorporating rocket motors) 2.10^{-8} per crane lift
(iron bombs) 2.10^{-10} per crane lift
(other munitions) 2.10^{-9} per crane lift

ship striking accidents:
(munitions incorporating rocket motors) 2.10^{-9} per ship passing
(iron bombs) 2.10^{-11} per ship passing
(other munitions) 2.10^{-10} per ship passing

ship collision accidents:
(munitions incorporating rocket motors) 2.10^{-8} per ship passing
(iron bombs) 2.10^{-10} per ship passing
(other munitions) 2.10^{-9} per ship passing

It must be emphasized that these rates were derived for the particular port of study handling specific types of munitions and are not necessarily appropriate for use elsewhere.

The rates derived for initiating events were converted into estimates for the annual probability of there being an explosion in the port. This was done by multiplying the rates by the number of explosives loads moved through the port annually. An example of this type of calculation is given below - this considers the probability of an explosion in the port as a result of a fire igniting on a road trailer carrying ammunition between the rail terminal and the berth.

The rate of ignition of cargo-damaging fires on road trailers travelling through the port was estimated to be: 2.10^{-10} per vehicle-km

The length of the route between the rail terminal and the berth in the port is
approximately: 2km

The number of ammunition containers transported on road trailers between the rail terminal and the
berth in 1993 was approximately: 2000

The product of these three numbers gives an estimate for the annual probability of there having been an
explosion due to the stated cause. The value obtained is 8.10^{-7}, ie about one chance in 1 ,250,000 per
year. Similar types of calculations were performed for the other types of accidents considered.

In mathematical terms:

$$Prob= \sum_{i=1}^{i=n} A_i * L * P(I \mid A_1)$$

where Prob   is the annual probability of an explosive event involving a
                                    particular type and size of explosives load,

n   is the total number of accident types considered,

L   is the number of loads of the specific type and size moved
                                    through the port annually.

A_i is the rate at which the explosives load is affected by
                                    accident type i,

$P(I \mid Ai)$ is the conditional probability that the load would initiate
                                    given its involvement in accident type i,

In addition to the possibility of explosive events arising from fire and impact accidents, such
events could also occur spontaneously as a result of an initiation of an unsafe item in an
explosives load. It is not an easy matter to derive values for the rates with which such events
might potentially occur. Although a number of such accidents have occurred in the past,
lessons have been learnt from these accidents and measures have been taken to try to prevent
their recurrence. It is tme, however, that safety flaws in the design and packaging of
explosives items sometimes only come to light with the occurrence of accidents; it may be
assumed that this will continue to be the case in the future. In the present study, it has been
possible to do no more than examine the historical accident record for the transportation of
explosives in order to draw some broad conclusions about the relative threat posed by unsafe
explosives. In fact, the historical record for the UK shows that unsafe explosives are as likely
a source of transportation events as fire and impact accidents. Based on this observation, an
allowance for the risks of unsafe explosives has been made by simply doubling the explosive
event probabilities derived for the fire and impact accidents.

<u>The Consequences of Explosives Events</u>

The number of fatalities (if any) that would be caused by an explosion in a port would depend on the types and quantities of explosives initiated and the numbers of people in the vicinity of the explosion. In general, the range over which the lethal effects of an explosion would extend would increase with the explosibility and quantity of explosives initiated. A number of explosion effects models have been developed which allow values to be estimated for the ranges at which certain levels of lethality might be expected from initiations of particular types and sizes of explosives loads.

A number of these explosion effects models were used to predict the relationship between distance from an explosion and lethality, taking into account the effects of blast, fragments and thermal radiation. The results were then combined to produce estimates for the range at which the following fatality probabilities could be expected: 100%, 90%, 50%, 10% and 1 %. The numbers of persons withih these hazard ranges during normal operation of the port were then established. These numbers varied with both time of day and day of the week and were found to be at a minimum during the hours 24:00 - 06:00. The analysis also took account of the possibility that some types of accidents might not inimediately result in an explosive event and that in such cases there may be time for personnel to be evacuated to a place of safety before the occurrence of an explosion. For example, fires on board ships could be expected to escalate only gradually (in the event that fire-fighting action were to be unsuccessful) and in such circumstances it could be expected that there would be a reasonable chance that workers present at the berth at the time of ignition would be evacuated to a place of safety before any subsequent explosion.

Fatality estimates were calculated by determining the numbers of persons who could be expected to be within the areas bounded by the hazard ranges of the explosives loads at the time of initiation and then multiplying those numbers by the average fatality probability for the area. The process can be expressed mathematically as follows:

$$NT = N_{100} + 0.95.(N_{90} - N_{100} + 0.7.(N_{50} - N_{90} + 0.3.(N_{10} - N_{50}) + 0.05.(N_{01} - N_{10})$$

where N_T is the total number of fatalities expected,
        N_{100} is the number of persons within the 100% lethality range,
        N_{90} is the number of persons within the 90% lethality range,
        N_{50} is the number of persons within the 50% lethality range,
        N_{10} is the number of persons within the 10% fatality range,
        N_{01} is the number of persons within the 1% fatality range.

The consequence analysis showed that an explosion at the port's rail terminal during the daytime (08:00 - 18:00) could result in many fatalities, as large numbers of people work in offices near the rail terminal during these hours. Most of these offices are unoccupied at night. Thus the numbers of persons at risk from operations at the rail terminal could be minimized by switching to nighttime working.

RESULTS AND DISCUSSION

Calculation of risk estimates

Risks were determined by combining estimates for the likelihood of different types and sizes of explosive events occurring in the port with estimates for the consequences of those events. The results are expressed in the form of FN curves, which show the estimated annual probability (F) of accidents resulting in N or more fatalities. Separate curves were constrncted for daytime and nighttime operations and these are shown in Figures 1 and 2 respectively. The two curves are compared in Figure 3.

Significance of the results

It will be seen that the FN curve for daytime operations extends out to more than 100 fatalities while that for daytime operations cuts off at about 20 fatalities. This result is explained by the lower numbers of people in the vicinity of the port's rail terminal at night compared with during the day. During normal working hours, 160 persons would typically be present in offices within 112 meters of the mid-point of the rail terminal, while at night these numbers drop to just three. If an explosion were to occur without warning in this area during daytime working hours, it could be expected that in excess of 100 persons would be killed. However, an accidental explosion in the worst possible circumstances at night would result in less than 20 fatalities.

It will also be seen that the two curves merge at low N. This result is explained by the fact that the same numbers of persons are required to move explosives during the night as during the day; hence the number of fatalities that could be expected among these workers in the event of an accidental explosion would be independent of the time of day the explosion occurred.

The results suggest that the chance of there having been a fatal explosion in the port from the handling of ammunition undertaken as part of the 1993 military drawdown program was of the order of 1.10^{-4}, A, ie one chance in 10,000. This estimate is intentionally conservative for various reasons previously outlined. It is not the purpose of this paper to evaluate the acceptability of this risk, but it may be put into context by comparison with the chance of a fatal accident in the port due to the chemical trade, which has previously been assessed at about 5. 10-~, or about one chance in 200 per year[5]

Optimization of safetv

The switch to nighttime working is clearly an important measure that complies with the principle of reducing risks to a level that is as low as reasonably practicable. This reduces the numbers of people exposed to risk from operations at the rail terminal. The improvement in the risk levels is most clearly demonstrated by comparing the overall number of statistical fatalities expected each year from nighttime and daytime operations: $1.7.10^{-3}$ and $5. 3.10^{-4}$ respectively - a threefold improvement for nighttime working.

Nighttime working provided an additional safety benefit in that ammunition ships left the berth at times when they were unlikely to pass passenger vessels in the navigation channel of the harbor. As part of the present study, an assessment was made of the chance that a passenger vessel would be badly affected in the event of an explosion in the harbor's navigation channel. The probability of such an event was found to be very remote. Nonetheless, the Port of Felixstowe has taken measures to eliminate this risk entirely. These measures provide for effective segregation of explosives-carrying vessels and passenger vessels. The details of these measures are as follows:

(I)   No explosives vessel (for this purpose defined as a vessel carrying in excess of 50 tonnes NEQ of HD 1. 1, 1.2 or 1.3 explosives) is allowed to pass a passenger vessel (defined for this purpose as a vessel carrying in excess of 12 passengers) or another explosives vessel in the main deep water channel of the harbor.

(ii)   A minimum buffer zone of 5 cables (about 0.5 miles) is enforced between an explosives vessel and a passenger vessel travelling in the same direction through the harbor.

(iii)   If conflict of movement between explosives vessels and passenger vessels arises, the Harbor Master is to instmct the explosives vessel to remain alongside the berth, or not to enter the harbor, as the case may be, until clear transit within the above rnles is possible.

CONCLUSIONS

The quantitative risk assessment identified a number of safety issues not normally considered. In particular, the QRA highlighted the potential risk to passenger vessels in the navigation channel of the harbor. Although the risk of an accident involving a passenger vessel was assessed to be extremely low, the operators of the Port of Felixstowe have instituted an appropriate traffic management system to eliminate this risk entirely.

QRA is not normally applied to licensed ports in the UK, but the above study has shown that it can make a useful contribution to the safe handling of explosives in these locations. However, the study required significant and specialized resources and this would militate against the use of full QRA in all licensed ports. These difficulties not withstanding, there may be scope for incorporating elements of QRA into the existing licensing technique as further experience is gained in the application of QRA to explosives safety. This may ultimately lead to a more flexible approach to licensing ports than the current procedure which is based on Quantity-Distance principles[4].

REFERENCES

1   UK Health and Safety Executive, 'Risk criteria for land-use planning in the vicinity of major industrial hazards', HMSO, London, 1998, ISBN 0 11 885491 7.

2   Moreton, P A 'An investigation of the relative risks of transporting blasting explosives by road in maximum size loads of Ste and 16te', HMSO, London, 1993, ISBN 0-853563861.

3   UK Health and Safety Executive, 'The Peterborough explosion', HMSO, London, 1990, ISBN, 0 11 8855727.

4   Merrifield, R and Moreton, P A, 'An Investigation of the feasibility of using risk assessment methodology for licensing explosives handling ports', Minutes of the 25 Explosives Safety Seminar, Anaheim, California', Department of Defense Explosives Safety Board, Virginia, 1992.

5   UK Health and Safety Commission, 'Major hazard aspects of the transport of dangerous substances, Report and Appendices', HMSO, London, 1991, ISBN 0 11 885676 6.
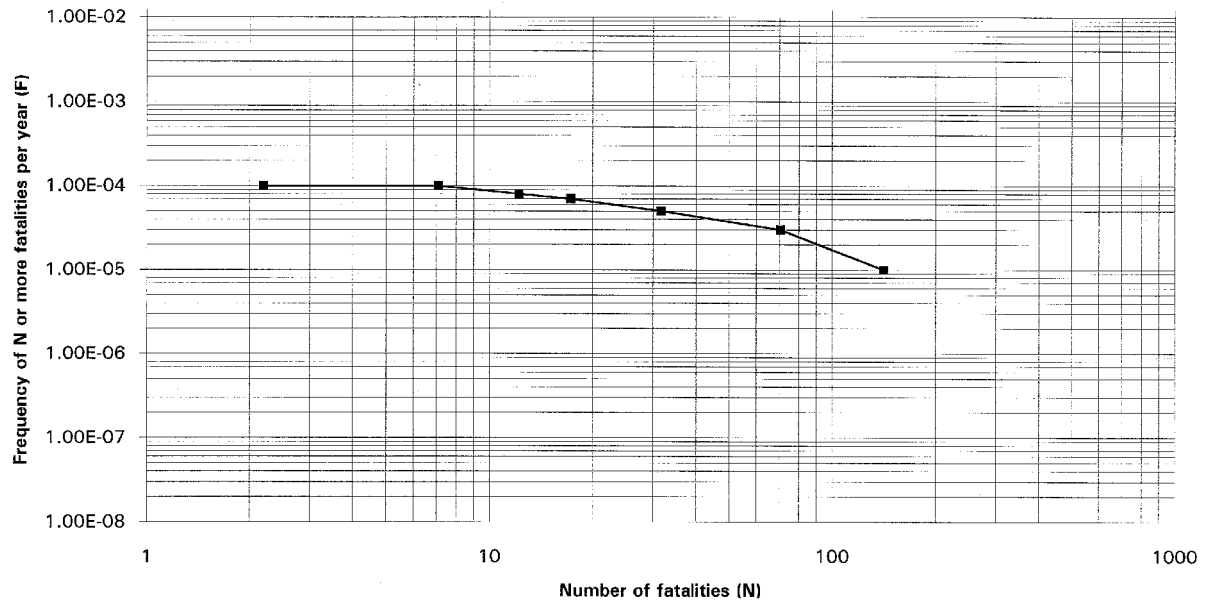
Figure 1: FN Curve for Daytime Operations

Figure 1 : FN Curve for Daytime Operations
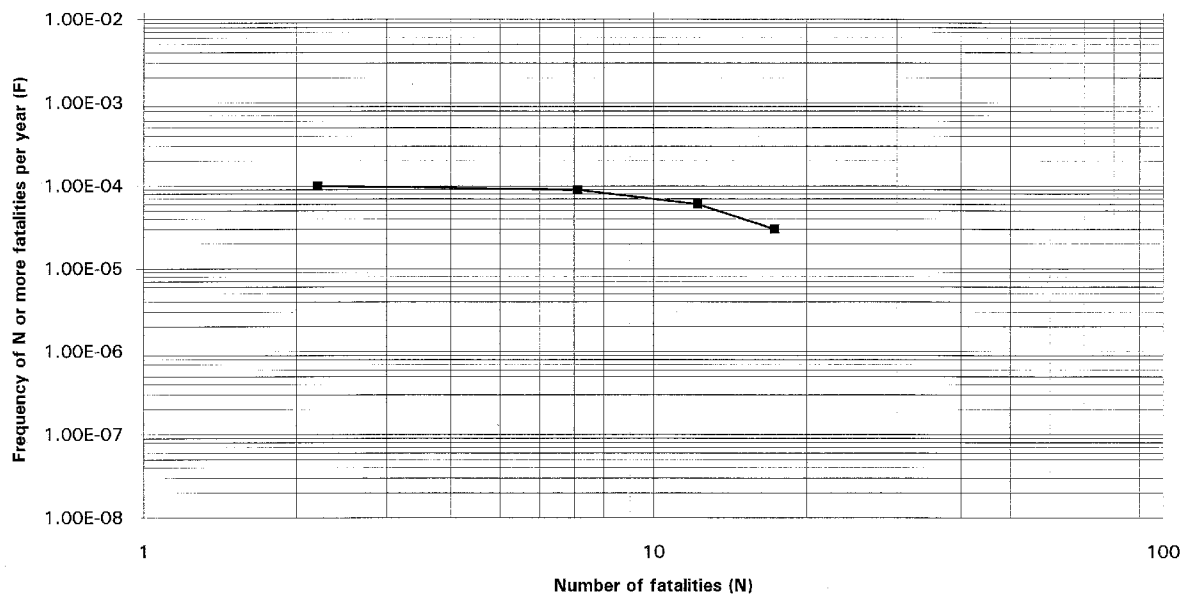
Figure 2: FN Curve for Nighttime Operations

Figure 2 : FN Curve for Nighttime Operations
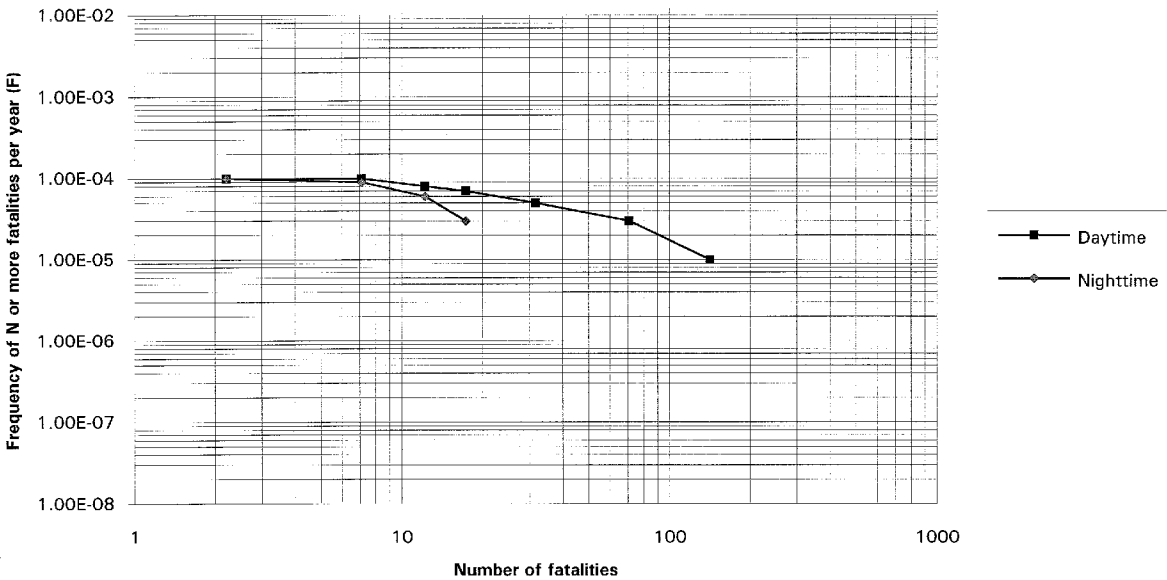
Figure 3: Comparison of Daytime and Nighttime Operations

Figure 3 : Comparison of Daytime and Nighttime Operations